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An ammonia emission inventory for fertilizer application in the United States

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Abstract

Fertilizer application represents a significant fraction of ammonia emissions from all sources in the United States. Previously published ammonia inventories have generally suffered from poor spatial and temporal resolution, erroneous activity levels, and highly uncertain emission factors. Here we present an ammonia emission inventory for fertilizer application that for the first time incorporates county-level data at monthly resolution, and includes more accurate activity levels and emission factors. The inventory shows that considerable variations in emissions can occur within a state. The emissions generally peak at two times of the year, in spring and in fall. The timing of these peaks depends on crop schedules. Overall, the new inventory shows the importance of determining emissions at sub-annual time resolution, and at spatial resolution better than statewide average values as reported in previous inventories.

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1. Introduction

Accurate prediction of ambient ammonia concentrations is important for several reasons. Along with gases such as NO_x, SO_x, and hydrocarbons, ammonia is a precursor to secondary aerosol, and it can combine with these other precursors to form chemical species such as ammonium nitrate and ammonium sulfate. These species are major constituents of PM 2.5, which has been linked to health effects. Ammonia also contributes to acid deposition and can lead to eutrophication (Sutton et al., 1995). Furthermore, evidence suggests that ammonia may lead to global warming (Bouwman et al., 1997).

Predicting ammonia concentrations requires an accurate emission inventory. The most significant source of ammonia in existing inventories is animal husbandry (Asman, 1992; Battye et al., 1994; Roe and Strait, 1998). Current inventories describe fertilizer application as a major contributor to emissions, usually listing it as the second most significant source (e.g., Battye et al., 1994; Bouwman et al., 1997). According to literature summarized by Battye et al. (1994), animal wastes and fertilizer together are responsible for 90% of anthropogenic ammonia emissions in Europe, and they hypothesize that the same is also true in the US. Estimates of the contribution of fertilizer to total emissions in the UK range from 3% to 21% (Sutton et al., 1995), while estimates of its contribution in the US are 7% (Roe and Strait, 1998) and 9.5% (Battye et al., 1994). An estimate of its contribution globally is 17% (Buijsman et al., 1987). Clearly, emissions from fertilizer constitute a sizable portion of total ammonia, and an accurate total inventory cannot be made without careful consideration of this category.

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2. Problems with existing inventories

Several ammonia inventories that include fertilizers have been published. However, these inventories suffer from a number of inadequacies. First, most of the existing inventories were developed with poor spatial resolution, often reporting a single value for an entire state. Fertilizer application is more intense in agricultural areas; consequently, a state-level inventory overestimates emissions in non-agricultural areas and underestimates emissions from farms. Even inventories that report emissions at the county level are inadequate for use with current atmospheric chemistry models that use grid cells as small as 2–4 km per side.

Second, published inventories do not have adequate temporal resolution, with many inventories providing only annual average values. Fertilizer application is seasonal and is related to planting and harvesting in the spring and fall, respectively. Because ammonia emissions are overwhelmingly released within a few days after application (Jarvis and Pain, 1990; Burch and Fox, 1989; Al-Kanani et al., 1994; Van der Weerden and Jarvis, 1997), ammonia emissions are also seasonal. A temporal resolution of 1 year overestimates emissions in the summer and winter and underestimates emissions in the spring and fall.

Third, the published inventories often use activity levels that are prone to error. Many of these activity levels are based on sales of fertilizer to dealers rather than to farmers. The dealers may subsequently sell the fertilizer to farmers in other locations, resulting in an inaccurate spatial distribution of activity levels. A better approximation (in the absence of actual application data) is to use sales from dealers to farmers.

Finally, some inventories do not account for variations in emission factors from different kinds of fertilizer. For example, the National Acid Precipitation Assessment Program (NAPAP) inventory incorporated emissions from only anhydrous ammonia (Battye et al., 1994). To properly estimate ammonia emissions, the major types of fertilizer and their respective emission factors must be accounted for.

3. Methodology

3.1. Activity levels

Data on the amounts of fertilizer applied to land surfaces are not recorded by the US Department of Agriculture (USDA). However, the USDA reports that data on fertilizer sales to farmers are a reliable approximation of the amounts applied (D. Terry, pers. comm.; H.H. Taylor, pers. comm.). Two sources of fertilizer sales data have been used in this study. The Association of American Plant Food Control Officials

(AAPFCO) maintains a database that lists county-level sales of various types of fertilizer (AAPFCO, 1995). This database was used to generate the current national inventory (Roe and Strait, 1998). AAPFCO data are based on direct sales to farmers instead of sales to dealers and are recorded for the periods of January–June and July–December for years 1985–2000. It is recognized that time lags occur between purchasing and application; however, this is considered to be insignificant, as farmers generally apply fertilizer in the same season in which it was purchased. The second database is from the US Geological Survey (USGS) and lists fertilizer sales to farmers by county for the years 1987–1991 (Battaglin and Goolsby, 1994). USGS obtained data on fertilizer sales at the county level for 1987 and at the state level for 1988–1991. Data at county-level resolution for the years 1988 through 1991 have been estimated by USGS by applying the ratio of county fertilizer sales in 1987 to state fertilizer sales in 1987, and then multiplying this ratio by total fertilizer sales in the state for the year of interest. Data are available for 1-year periods.

AAPFCO activity levels are considered to be more accurate for two reasons. First, USGS data do not exist for years after 1991, and the USGS county data for years 1987–1991 are not true county figures, but are state figures that have been allocated to the county-level according to the 1987 county/state ratio. Second, the AAPFCO data sets contain a more detailed breakdown of fertilizer use by type. These data sets list the quantity of fertilizer used for each of almost 200 types. In contrast, USGS lists the quantities of the four major types of fertilizer used and then aggregates the remaining quantities of fertilizer into a single ‘miscellaneous’ category. Thus, activity levels from AAPFCO have been used for the 26 states for which county-level data are available, which fortunately are the more agriculturally intensive states. For the remaining states, only statewide rather than county-level data are available from AAPFCO. Thus, the county ratios from USGS have been multiplied by these state-level values from AAPFCO to determine activity levels for each of those states.

3.2. Emission factors

Values of ammonia emission factors from fertilizer are typically expressed as a percentage of nitrogen applied that volatilizes as ammonia. Several authors have reported empirical ammonia volatilization rates as functions of windspeed, soil pH, and soil moisture content (Whitehead and Raistrick, 1990; Kirk and Nye, 1991; Terman, 1979). Others have developed mathematical models to calculate emission factors under varying parameters (e.g., Ismail et al., 1991; Bock and Kissel, 1988). However, using these relations requires collecting large amounts of data. Therefore, as has been done with

past published inventories (e.g., Battye et al., 1994), this inventory uses average emission factors for each type of fertilizer, and does not attempt to correct for environmental conditions.

Based on a literature review of published emission factors, it appears that Asman (1992) provides the most up-to-date and reliable factors for most types of fertilizer. This source has been used by other inventories (Bouwman et al., 1997; Battye et al., 1994). Emission factors from Asman (1992) have been used here for all types of fertilizer except nitrogen solutions. This category is typically a mixture of urea and ammonium nitrate in approximately a 1:1 ratio (Follett, 1989). Urea has an emission factor of 15% and ammonium nitrate an emission factor of 2% (Asman, 1992); therefore, the emission factor for urea-ammonium nitrate should logically fall between these two limits. Values in the range 4.8–19% and 0.3–19% have been reported by Al-Kanani et al. (1990, 1991). Oenema (pers. comm.) suggests a value of 5–10% when the fertilizer is broadcast, and <4% when injected. Two emission factors have been reported for nitrogen solutions, Asman (1992) and the European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC, 1994). The former gives a value of 2.5% and the latter a value of 8%. The first value is believed to be uncertain: nitrogen solutions are used only infrequently in Europe, and thus little time was devoted to developing a reliable emission factor for this type of fertilizer (W.A.H. Asman, pers. comm.). Since nitrogen solutions fertilizer is more frequently broadcast than injected, and since the overall average of the above values is about 8%, the ECETOC (1994) value of 8% has been used here. However, the simulation was run a second time using the emission factor of 2.5% for comparative purposes, with results given at the end of this paper.

Of the nearly 200 types of fertilizer that are used in the US, 13 types comprise roughly 96% of all fertilizer use. The emission factors for minor types of fertilizer are not as reliable. Quantities of these minor types have been combined into a “miscellaneous” category and assigned an emission factor equal to the weighted average emission factor for all major fertilizers. Table 1 lists the emission factors used in this inventory.

3.3. Spatial allocation

In order to provide the higher spatial resolution that can be accommodated by today's atmospheric chemistry models, the GIS application ARCVIEW has been used to build the inventory. ARCVIEW can incorporate land use maps that show cropland areas within each county. Through the use of these maps, the total ammonia emissions calculated for each county can be allocated to the specific cropland areas from which they originate. The land use maps chosen were from the EPA GIRAS

data set. These are maps that were originally digitized from satellite photos by the USGS and later converted to ARCVIEW format by the EPA. The maps are based on the Anderson land use scheme, where one land use code is provided specifically for cropland.

Although most of the EPA GIRAS maps date back to the late 1970s and early 1980s, the locations of cropland generally have not changed over the past 20 years (H.H. Taylor, pers. comm.). The main exception is suburban development near cities. Since photochemistry around urban areas may influence the secondary formation of ammonia-containing particles, the effect of urban sprawl could be significant. However, it should be noted that inaccuracies due to land use changes in these areas will affect only the sub-county spatial resolution of the emissions, not the accuracy of the emissions themselves.

3.4. Temporal allocation

Since records are not kept on fertilizer application dates, one must examine information on crop planting schedules and use typical fertilizer application rates and recommended application timing to generate a temporal distribution. For the current inventory, the total number of acres planted with principal crops for each state in 1995 has been obtained from USDA (USDA-NASS, 1998a, b, 1999a, b). Other data have also been obtained from the USDA: the total number of acres planted with a crop has been multiplied by the percent of acres receiving nitrogen and by the average amount of nitrogen applied per acre to compute the total amount of nitrogen applied to that crop for each state. National averages have been used for some states with low production where state-specific data are not available. Note that we could have used these USDA values instead of the AAPFCO and USGS activity level data to calculate the total amount of nitrogen applied to all crops in each state. This has not been done, as the AAPFCO and USGS data are more reliable and have better spatial resolution. For quality assurance, however, the results from this method have been compared with the activity levels from AAPFCO and USGS, and agreement is generally good.

To illustrate, the original data from USDA-NASS (1997) show that 9.75 million acres of soybeans were planted in Illinois in 1995, and 17% of these acres received nitrogen at an average rate of 24 lbs N per acre. We thus calculate that 39.8 million lbs of N has been applied to soybeans in Illinois on 1.66 million acres.

The USDA categorizes fertilizer application into four time periods: “spring before planting,” “at planting,” “after planting,” and “fall before planting.” According to the USDA, the first period represents approximately 1 month before planting, and the third period represents approximately 1 month after planting (W. Huang, pers. comm.; H.H. Taylor, pers. comm.). The last period

Table 1
Calculation of NH₃ released for Illinois, Jan–Jun

Fertilizer type	Total fert. applied Jan–Jun (a)	Fertilizer application (%) (b)						Emission Factor (c) (%)	NH ₃ released (d) = (a) × (b) × (c) × (17/14)					
		Jan (%)	Feb (%)	Mar (%)	Apr (%)	May (%)	Jun (%)		Jan (10 ³ kg)	Feb (10 ³ kg)	Mar (10 ³ kg)	Apr (10 ³ kg)	May (10 ³ kg)	Jun (10 ³ kg)
Multi-nutrient fertilizer	13,600	0.1	0.1	21	52	10	17	4	0.66	0.66	139	343	66	112
Anhydrous ammonia	219,000	0.1	0.1	21	52	10	17	1	2.7	2.7	558	1380	266	452
Aqueous ammonia	0	0.1	0.1	21	52	10	17	1	0	0	0	0	0	0
Ammonium nitrate	8540	0.1	0.1	21	52	10	17	2	0.21	0.21	44	108	21	35
Ammonium sulfate	7450	0.1	0.1	21	52	10	17	8	0.72	0.72	152	376	72	123
Ammonium thiosulfate	413	0.1	0.1	21	52	10	17	2.5	0.013	0.013	2.6	6.5	1.3	2.1
Calcium amm. nitrate	41	0.1	0.1	21	52	10	17	2	0.001	0.001	0.21	0.52	0.10	0.17
Nitrogen solutions	173,000	0.1	0.1	21	52	10	17	8	17	17	3530	8740	1680	2860
Urea	36,400	0.1	0.1	21	52	10	17	15	6.6	6.6	1390	3450	663	1130
Diammonium phosphate	38,400	0.1	0.1	21	52	10	17	4	1.9	1.9	392	970	187	317
Monoammonium phosphate	3500	0.1	0.1	21	52	10	17	4	0.17	0.17	36	88	17	29
Liquid ammonium polyphosphate	2620	0.1	0.1	21	52	10	17	4	0.13	0.13	27	66	13	22
Potassium nitrate	20	0.1	0.1	21	52	10	17	2	0.0005	0.0005	0.10	0.25	0.049	0.083
Miscellaneous fertilizer	2870	0.1	0.1	21	52	10	17	5.7	0.20	0.20	42	103	20	34
Total ^a									30	30	6310	15,600	3010	5120

Note: Note that a similar table exists for Illinois for Jul–Dec, but is not shown here.

^aThe numbers shown in the “Total” row should be the same as the numbers for Jan–Jun for Illinois in Table 2. The differences are due to the accumulated rounding errors from each step in Table 1.

occurs after the preceding year's crop has been harvested and after the soil temperature has dropped below 50°F, but before heavy frosts. For each period, the percent of acres receiving fertilizer in that period has been multiplied by the average amount of nitrogen applied in that period. Results for the four time periods have then been used to calculate the percentage of total nitrogen applied during each period.

To illustrate, the original data (USDA-NASS, 1997) show that 53% of the 1.66 million fertilized acres planted with soybeans in Illinois received nitrogen fertilizer in the spring before planting, 6% at planting, 3% after planting, and 38% in the fall before planting. The average application rate of nitrogen per acre for each time period is 23, 49, 6, and 22 lbs, respectively (USDA-ERS, 1996–1997). After multiplying these two parameters to get total nitrogen applied in each period and then normalizing over all periods to compute percentages for each period, it is estimated that 51%, 12%, 1%, and 36% of total fertilizer applied to soybeans in Illinois was applied in the spring before planting, at planting, after planting, and in the fall before planting, respectively.

To determine dates of fertilizer application, crop schedules have been obtained from the USDA that specify the usual planting and harvesting dates for each of the major crops of every state. These dates represent the period in which at least 90% of crops are either planted or harvested, respectively, which typically lasts several weeks to 2 months (USDA-NASS, 1997). Fertilizer application timing has then been allocated monthly by matching percentages in each of the four time periods for a crop with its corresponding planting and harvesting schedule. The “at planting” percentage is spread over the usual planting dates. Based on the discussion above, the “spring before planting” percentage is spread over a period of time that is the same number of days as the usual planting period, but adjusted to be 1 month earlier in the year. The “after planting” percentage is spread over a period of time that is the same number of days as the usual planting period, but adjusted to be 1 month later in the year.

The “fall before planting” percentage has been allocated using harvesting dates. For crops harvested in late September or after, it is assumed that soil temperatures would be below 50°F, and that farmers apply fertilizer as soon as possible after harvesting to avoid the first frost. Therefore, for this situation, the percentage for “fall before planting” has been spread over a period of time that is the same number of days as the active harvesting period, but adjusted to be 1 month later in the year. For crops harvested before late September, the percentage for “fall before planting” has been spread over September and October, under the assumption that soil temperatures would drop below 50°F during these months and again under the assump-

tion that farmers would apply fertilizer in the early fall to avoid the first frost. After allocating the four time periods accordingly, the result is, for each month, a percentage of the total amount of fertilizer applied.

To illustrate, the original data from USDA-NASS (1997) show that the most active planting dates for soybeans in Illinois last from 6 May to 16 June, and the most active harvesting dates last from 23 September to 3 November. Thus, the “spring before planting” percentage of 51% has been spread over the period of time between 6 April and 16 May, while the “at planting” percentage of 12% has been allocated to the period of time between 6 May and 16 June. The “after planting” percentage of 1% has been spread over the period of time from 6 June to 16 July, and the “fall before planting” percentage of 36% has been allocated to the period of time between 23 October and 3 December. Thus, of the total nitrogen applied to soybeans in Illinois, 31% is assumed to be applied in April, 28% in May, 5.3% in June, 0.30% in July, 7.2% in October, 26% in November, and 2.5% in December. This procedure has been applied to all crops except winter wheat and hay.

Winter wheat differs from other crops in that it is planted in the fall, and 1 month after planting corresponds to early winter. Following recommendations of fertilizer experts Epplin (pers. comm.) and Huang (pers. comm.), the “after planting” percentage for winter wheat is spread over February and March (with 25% being allocated to February and 75% to March) for states south of the latitude of southern Illinois, and over March and April (with 75% being allocated to March and 25% to April) for states north of this latitude. The other exception to the algorithm above is hay, for which the times of fertilizer application are not given by the USDA (W. Huang, pers. comm.). Thus, forage experts in different US regions have been contacted to estimate the times of fertilizer application for hay (D. Ball, pers. comm.; J. Gerrish, pers. comm.; J. Slater, pers. comm.; and W. Huang, pers. comm.). It is estimated that $\frac{1}{30}$ of the total amount of fertilizer applied to hay is applied in each of January, February, October, November, and December, $\frac{1}{12}$ is applied in each of May, June, July, and August, and $\frac{1}{6}$ is applied in each of March, April, and September.

For each crop, the estimated amount of fertilizer applied during the year has been multiplied by the percentage applied each month. The resulting amounts of fertilizer are then summed over all crops and normalized to the total amount of fertilizer used over each 6-month period for which activity level data exist to compute a percentage of the total fertilizer applied each month.

For soybeans in Illinois in May, 39.8 million lbs of N is multiplied by the 28% applied that month. The product, 11.1 million lbs of N, is added to the results for

other crops for May and normalized to the total fertilizer used for all crops in the 6-month period, along with the other months from January through June. This results in a final estimate that 10% of all fertilizer used in Illinois in the first 6 months of the year is applied in May (column “b” in Table 1).

Each monthly percentage is then multiplied by the amount of fertilizer applied as obtained from AAPFCO or USGS (column “a” in Table 1), and then multiplied by the emission factor corresponding to each type of fertilizer (column “c” in Table 1). Numerous studies have shown that the majority of ammonia emissions are released from fertilizers within several days of application (Jarvis and Pain, 1990; Burch and Fox, 1989; Al-Kanani et al., 1994; Van der Weerden and Jarvis, 1997), and thus emissions have been treated as occurring simultaneously with application. Final results for each type of fertilizer are then summed to compute the total emissions released each month.

Citing Illinois as an example, Table 1 shows a final value of 3010 metric tons of ammonia released in May in Illinois. Note that the numbers in column “d” have been multiplied by 17/14 to account for the molecular weight conversion from N to NH_3 .

4. Assumptions and limitations of results

4.1. Temporal allocation

Crop schedules and times of fertilizer application are provided by the USDA for an entire state. Thus, the temporal allocation of fertilizer use in this inventory reflects averages over each state.

Further limitations on temporal allocation arise from a paucity of fertilizer application data. Although hay is an important US crop, constituting more planted acres than winter wheat in 1996 (USDA-NASS, 1997), the times of fertilizer application for this crop are not given by the USDA (W. Huang, pers. comm.). It has been necessary to rely on opinions of experts rather than published data for hay.

Fertilizer application timing data are available only for major crops; in 46 of the continental states, this constitutes 70–99% of all planted acres in the state, including hay. However, in Florida and California, citrus fruits comprise a large portion of planted acres, and fertilizer timing data do not exist for these crops. Therefore, temporal allocation was based on 27% and 58% of all planted acres for Florida and California, respectively. Note that this shortcoming does not affect total annual emissions but rather only the temporal allocation of those emissions.

Furthermore, fertilizer application timing data are available only for the major producing states of each crop. Therefore, a method was needed to estimate the

timing of fertilizer application for those states without data. Four methods were devised: (a) using data from neighboring states for the crop in question, (b) using data from states with roughly the same latitude for the crop in question, (c) using data from all states for the crop in question, and (d) using data from neighboring states for all crops planted in the same season. Each of these methods has been used to estimate fertilizer application timing for several states where actual timing data are available (Minnesota, Illinois, and Arkansas). Statistical analysis showed that method (a) yields the best results, but that method (c) is almost as good. Thus, method (a) has been used when data from neighboring states are available, and method (c) has been used elsewhere.

4.2. Fertilizer preferences

This inventory does not take into consideration fertilizer preferences exhibited by farmers for certain crops. Although anhydrous ammonia is the type of fertilizer used most on winter wheat, and nitrogen solutions is the type of fertilizer used the most on corn (USDA-ERS, 1996–1997), methods used here assume that both crops have these types of fertilizer applied in the same proportion. This assumption leads to small inaccuracies in emission estimates for some crops, resulting in a slight shift in the temporal allocation. Using the sparse data available on fertilizer preference, a few simulations have been run to determine the size of these errors. For three states, each in a different latitude band, results that take fertilizer preference into account have been compared with results that do not take preference into account. In nearly all cases, differences are negligible, ranging from near zero to a few percent. Only in cases of very low ammonia emissions in one state, where fertilizer is overshadowed by other sources, does fertilizer preference influence the temporal allocation.

4.3. Manure

The inventory developed here considers only ammonia emissions released by commercial fertilizers. Organic fertilizers applied to cropland, i.e., manure, have been neglected for several reasons. Most significantly, the amount of manure applied to commercial crops is far less than the amount of commercial fertilizer applied. In 1995, an average of 1 lb of manure was applied per acre of winter wheat, 2 lb for corn, and 3 lb for cotton, compared with 57 lb of commercial fertilizer applied per acre of winter wheat, 130 lb for corn, and 82 lb for cotton (USDA-ERS, 1996–1997). Furthermore, manure has a low nitrogen content, averaging about 0.03% nitrogen for manure from swine, 0.05% from beef and dairy cattle, and 0.35% from poultry (Ensminger, 1997).

In addition, data on the quantity of manure applied and the times of application are scarce, according to officials at USDA (M. Padgitt, pers. comm.), and the precise amount of nitrogen in manure varies according to the animals' diet (Ensminger, 1997).

Although manure application on fields results in ammonia emissions much lower than from commercial fertilizer, manure from confined animal feeding operations (CAFOs) can be significant. The majority of cattle, hogs, and chickens in the United States are raised in CAFOs. Manure generated on CAFOs is usually applied on adjacent land for growing crops to feed the animals. Ammonia emissions from this source are quite significant, and are typically counted in the animal husbandry sections of ammonia inventories.

5. Discussion

Figs. 1–4 show ammonia emissions for the United States for representative months of each of the four seasons, while Table 2 gives a full breakdown of emissions by state and month. The highest emissions occur in agriculturally intensive states in the Midwest. The southeastern coast and the Mississippi valley also exhibit high emissions during certain seasons.

Fig. 5 shows two peaks in fertilizer application, one in the spring and one in the fall. Fertilizer is rarely applied in the summer, since high temperatures increase

volatilization rates (Bouwman et al., 1997). Similarly, fertilizer is rarely applied in the winter, as frozen soil impedes absorption. Farmers often have more time in the fall and fertilizer prices tend to drop during this season, making the fall a popular time for applying fertilizer. Fig. 5 indicates that the annual average assumption used in previous inventories is reasonable for September and November, but poor for the other 10 months of the year. Indeed, for those 10 months the annual average assumption significantly underestimates or overestimates actual emissions. Perhaps most importantly, the annual average assumption is poor in the summer months of June through August, when air pollution is typically of most concern.

The complete results show that ammonia emissions from fertilizer application are dependent on regional crop schedules. The spring peak begins in March in the south-central US (from Texas through Missouri), and on both east and west coasts. In contrast, the spring peak does not begin until April in the colder northern Midwestern states (from Nebraska and the Dakotas eastward to New York), where crops are planted later. The southeast US shows very little difference in March and April.

Results also show that pockets of high emissions can occur in states not usually considered agriculturally intensive, and that emissions can vary greatly within a state or even a single county, although sub-county resolution is not shown in Figs. 1–4 for clarity. For

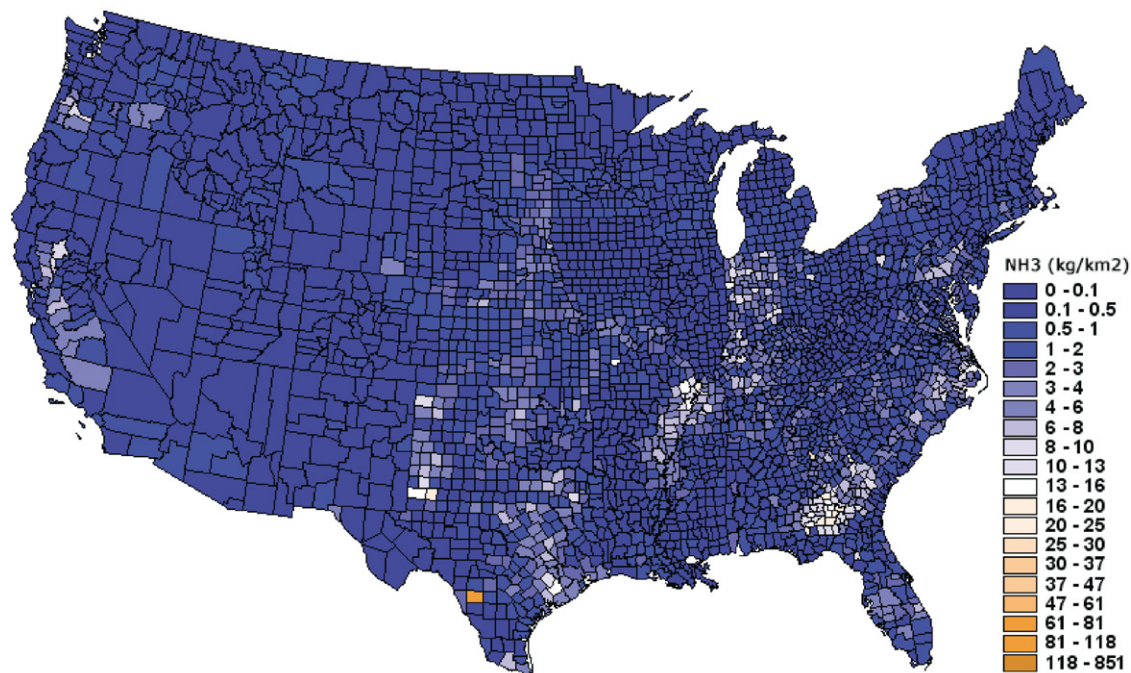


Fig. 1. Estimated ammonia emissions from fertilizer application in January 1995.

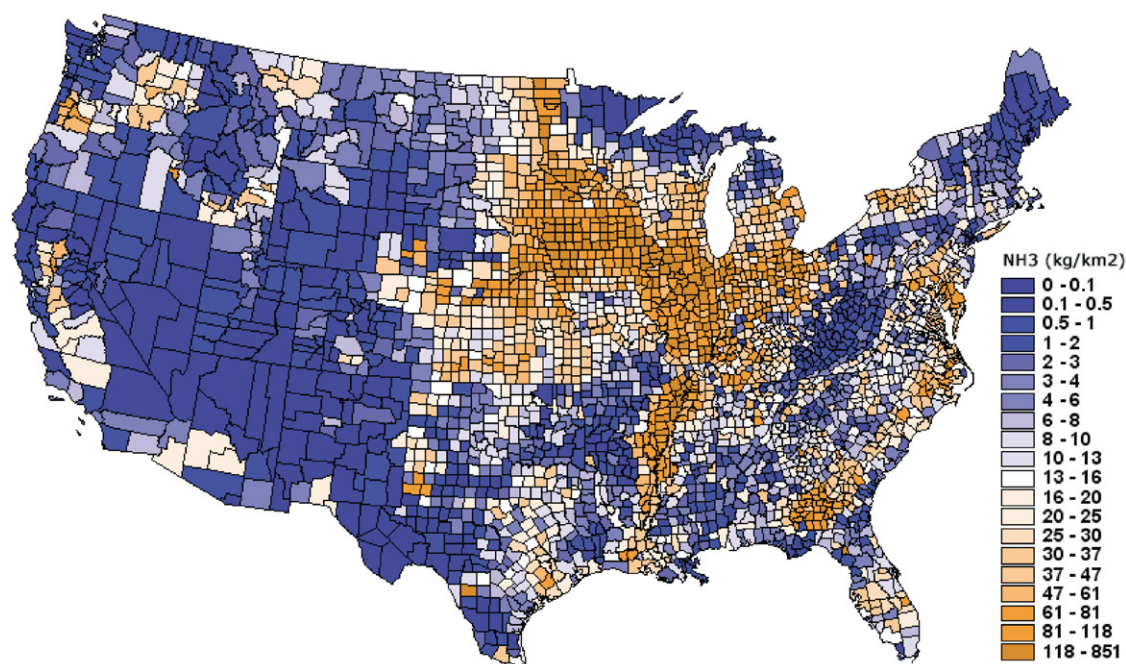


Fig. 2. Estimated ammonia emissions from fertilizer application in April 1995.

example, significant emissions are released in two pockets of Wyoming, one in the southeast corner of the state and one in the northwest, whereas the remainder of the state releases negligible emissions. In Florida, a state known for its production of citrus fruits, a small area emits a high level of ammonia, but the majority of the state releases low to medium emissions. Fig. 2 indicates that high ammonia concentrations can occur during the spring in the Houston, Chicago, and Fresno areas. If these elevated ammonia concentrations coincide with high concentrations of SO_2 or NO_x , under the appropriate meteorological conditions, these conditions could exacerbate ozone levels in the early ozone season. The results demonstrate that spatial resolution at the county level or better is important.

A study of ammonia emissions from fertilizer application and native soils in California was recently published by Potter et al. (2001). That study incorporated both field measurements and computer modeling. The authors estimated total annual ammonia emissions for the state as 12,000 metric tons, compared with 35,000 metric tons reported here. The difference is probably due in part to their lower emission factors, 0.05–6% compared with 1–15% used here. The emission factors used by Potter et al. (2001) incorporated fertilizer application methods and soil pH specific to California. Results of the two studies are consistent in identifying the major source regions; for example, the San Joaquin Valley is a major emitter in both inventories.

When summed over the year 1995, total ammonia emissions from fertilizer in the continental US of 761,000 metric tons are in rough agreement with the estimate of 504,000 metric tons given by Battye et al. (1994). Overall, emissions from fertilizer are a significant fraction of the total ammonia emissions from all sources; furthermore, this ammonia is released as concentrated emissions, both spatially and temporally, and thus this source can be important in local and regional inventories.

For comparative purposes, results were recalculated using the emission factor for nitrogen solutions of 2.5% proposed by Asman (1992) instead of 8% proposed by ECETOC (1994). Total emissions in the continental US were estimated as only 590,000 metric tons. The significant difference highlights the importance of using an appropriate emission factor for major types of fertilizer.

6. Summary

Ammonia emissions from fertilizer application constitute a significant portion of the national ammonia inventory. For this reason, an updated emission inventory for ammonia has been developed for the United States. The new inventory contains higher resolution in terms of fertilizer type and temporal and spatial distributions. Ammonia emissions from fertilizer

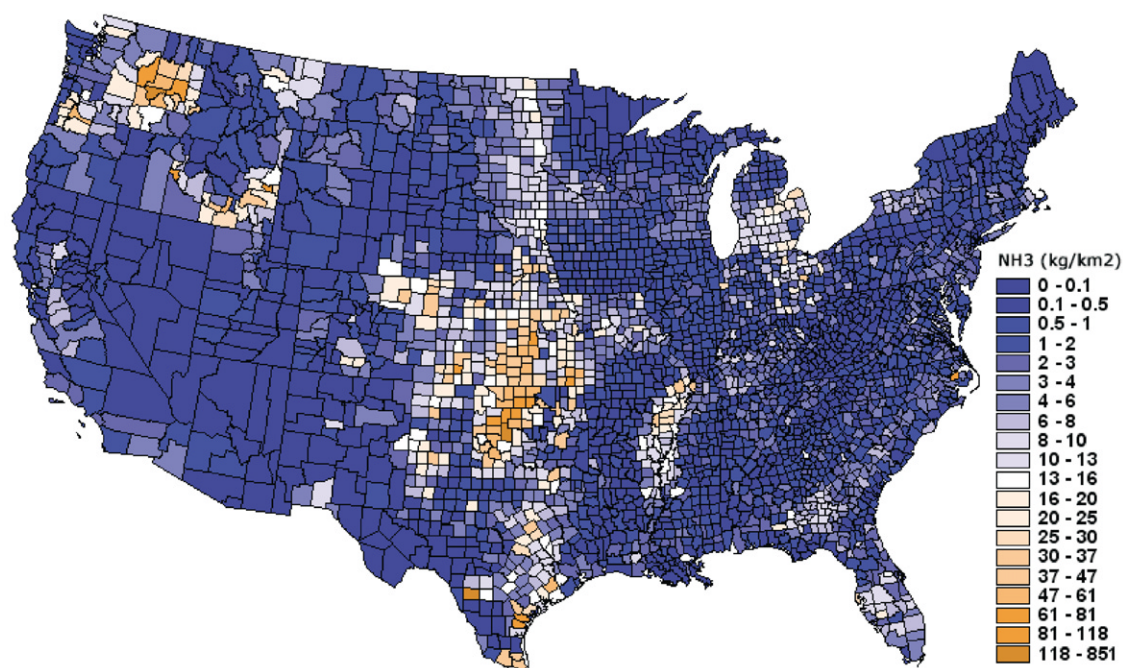


Fig. 3. Estimated ammonia emissions from fertilizer application in August 1995.

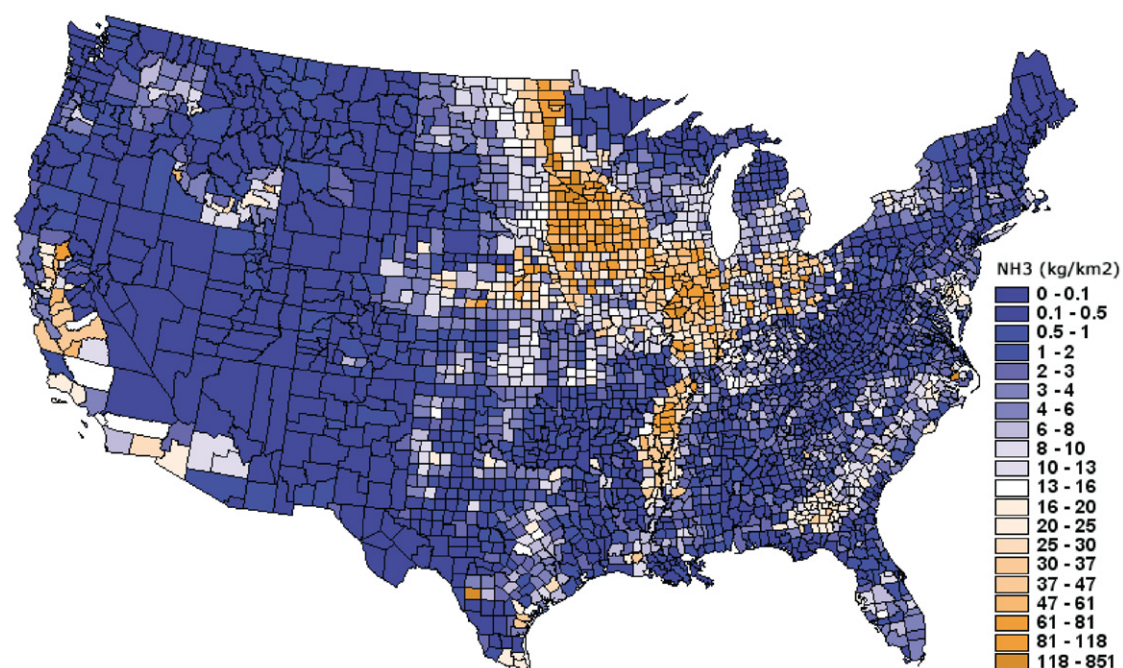


Fig. 4. Estimated ammonia emissions from fertilizer application in November 1995.

application have a high seasonal variation, and the new inventory addresses this by giving emission estimates on a monthly basis. In addition, land use maps have been

used to assign ammonia emissions from fertilizer application to the specific cropland areas within each county from which the emissions originate. This

Table 2

Monthly estimates of ammonia emissions from fertilizer application by state (in 10^3 kg)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alabama	113	252	914	1010	829	874	266	186	435	199	208	133
Arizona	36	65	224	1120	1950	933	143	137	273	488	699	725
Arkansas	211	1360	5460	3940	7140	8880	1190	673	1760	1620	2180	1490
California	372	599	3040	2490	8880	7220	1330	530	989	1130	3820	2450
Colorado	71	90	891	1470	954	1370	397	1480	717	83	437	455
Connecticut	24	24	118	134	73	73	25	23	45	11	12	9
Delaware	1	29	260	463	277	292	4	2	43	98	89	21
Florida	187	887	2050	1810	1630	1090	744	576	1170	592	386	334
Georgia	482	1110	2910	3110	3200	4910	746	299	974	823	812	575
Idaho	36	60	1680	1500	1230	1300	1190	1890	3500	2070	865	198
Illinois	28	28	6170	15,500	3100	5170	77	136	1080	1770	6270	3830
Indiana	395	406	5190	6000	5840	3450	1460	265	679	871	1680	1580
Iowa	34	34	5070	17,000	4120	3520	671	157	307	4050	8600	4820
Kansas	300	2910	13,100	6740	4000	3490	286	4340	5700	1340	1070	430
Kentucky	212	472	2900	3030	2400	2030	441	284	615	460	567	338
Louisiana	57	399	1350	2040	3930	5060	496	186	687	599	542	243
Maine	14	14	72	97	295	187	18	11	23	10	9	5
Maryland	27	109	734	1230	902	842	98	29	169	226	183	107
Massachusetts	15	15	78	164	122	130	101	58	119	70	70	23
Michigan	51	38	1210	2830	3470	6500	357	807	1560	376	599	516
Minnesota	83	83	3590	11,800	5280	2840	1750	478	3450	3400	9350	8270
Mississippi	73	111	1230	1610	2250	2570	1180	260	664	570	610	291
Missouri	343	1180	6000	4290	2880	2460	1120	953	2040	1950	1890	1710
Montana	91	91	1480	2270	1530	341	244	1160	2520	1430	125	94
Nebraska	231	125	3650	9000	4790	7080	503	1220	774	1080	2900	2770
Nevada	19	20	100	98	48	47	22	23	45	9	9	9
New Hampshire	6	6	29	52	35	35	21	13	26	13	13	5
New Jersey	16	16	118	238	279	206	109	40	78	26	71	67
New Mexico	32	90	529	432	437	369	75	316	190	21	50	39
New York	99	81	760	1920	1120	1260	322	224	431	87	388	561
North Carolina	295	304	3180	2830	2750	2630	428	265	667	798	863	416
North Dakota	26	26	729	2310	835	241	1040	894	13,900	8870	2030	804
Ohio	83	83	4680	5760	8050	11,100	4620	470	1520	729	1750	1410
Oklahoma	290	1550	5200	1370	946	827	424	4080	4860	688	234	225
Oregon	248	473	3660	2380	1160	864	349	1110	2240	739	207	189
Pennsylvania	185	132	966	1310	1270	2200	476	161	305	74	126	129
Rhode Island	1	1	6	18	17	20	4	2	3	3	3	1
South Carolina	82	322	919	877	652	956	152	150	477	438	421	206
South Dakota	184	184	1920	4350	2410	1780	699	803	1520	395	891	786
Tennessee	214	441	2520	2490	1490	1870	261	213	472	323	299	190
Texas	1500	4290	9970	7620	6270	3500	1960	4810	6720	5700	2450	1370
Utah	38	60	296	265	156	143	75	134	152	28	34	35
Vermont	11	11	57	114	85	80	16	8	16	10	10	3
Virginia	169	240	1580	1580	1230	995	180	168	407	257	181	137
Washington	39	268	1580	1280	901	522	108	3000	3760	789	275	154
West Virginia	16	18	90	95	65	81	31	22	45	11	11	11
Wisconsin	69	70	1140	3930	4770	3420	1020	294	395	75	784	781
Wyoming	104	95	532	644	354	334	276	247	509	125	156	158

inventory is an important component of the new CMU National Ammonia Emission Inventory, and will be especially useful to individuals (e.g., air quality modelers) who need higher resolution than that which exists in the current national inventory.

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Estimated Ammonia Emissions from Fertilizer Application in 1995

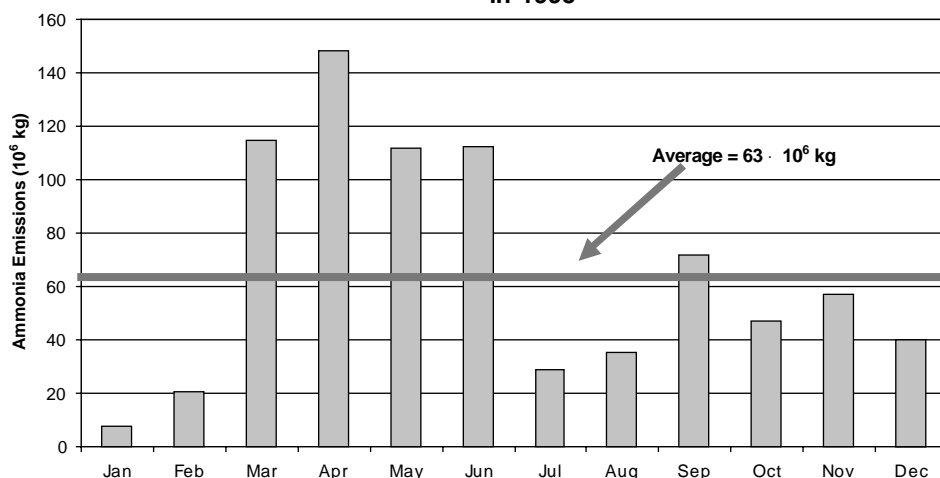


Fig. 5. Estimated Ammonia Emissions from Fertilizer Application in 1995.

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References

- Al-Kanani, T., Mackenzie, A.F., Blenkhorn, H., 1990. The influence of formula modifications and additives on ammonia losses from surface-applied urea-ammonium nitrate solutions. *Fertilizer Research* 22, 49–59.
- Al-Kanani, T., Mackenzie, A.F., Barthakur, N.N., 1991. Soil, water and ammonia volatilization relationships with surface-applied nitrogen fertilizer solutions. *Soil Science Society of America Journal* 55 (6), 1761–1766.
- Al-Kanani, T., MacKenzie, A.F., Fyles, J.W., Ghazala, S., O'Halloran, I.P., 1994. Ammonia volatilization from urea amended with lignosulfonate and phosphoroamide. *Soil Science Society of America Journal* 58 (1), 244–248.
- Asman, W.A.H., 1992. Ammonia emissions for Europe. Report no. 228471008 for National Institute of Public Health and Environmental Protection, Bilthoven, Netherlands.
- Association of American Plant Food Control Officials (AAPFCO), 1995. Commercial Fertilizers Database for 1995, Washington, DC.
- Battaglin, W.A., Goolsby, D.A., 1994. Spatial data in geographic information system format on agricultural chemical use, land use, and cropping practices in the United States. USGS. Water-Resources Investigations Report 94-4176.
- Battye, R., Battye, W., Overcash, C., Fudge, S., 1994. Development and selection of ammonia emission factors. Prepared by EC/R, Inc. for the US-EPA Atmospheric Research and Exposure Assessment Laboratory, Durham, NC.
- Bock, B.R., Kissel, D.E. (Eds.), 1988. Ammonia volatilization from urea fertilizers. Bulletin Y-206. Tennessee Valley Authority, National Fertilizer Development Center, Muscle Shoals, AL.
- Bouwman, A.F., Lee, D.S., Asman, W.A.H., Dentener, F.J., Van Der Hoek, K.W., Olivier, J.G.J., 1997. A global high-resolution emission inventory for ammonia. *Global Biogeochemical Cycles* 11 (4), 561–587.
- Buijsman, E., Maas, H.F.M., Asman, W.A.H., 1987. Anthropogenic NH₃ emissions in Europe. *Atmospheric Environment* 21 (5), 1009–1022.
- Burch, J.A., Fox, R.H., 1989. The effect of temperature and initial soil moisture content on the volatilization of ammonia from surface-applied urea. *Soil Science* 147 (5), 311–318.
- Ensminger, M.E., 1997. Beef Cattle Science. Interstate Publishers Inc., Danville, IL.
- European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC), 1994. Ammonia emissions to air in western Europe. Technical Report 62, Brussels, Belgium.
- Follett, R.F. (Ed.), 1989. Nitrogen Management and Groundwater Protection. Elsevier, New York, NY.
- Ismail, K.M., et al., 1991. Modeling ammonia volatilization from loamy sand soil treated with liquid urea. *Transactions of the ASAE* 34 (3), 756–763.
- Jarvis, S.C., Pain, B.F., 1990. Ammonia volatilisation from agricultural land. The Fertiliser Society (London), Proceedings No. 298, Peterborough, United Kingdom.
- Kirk, G.J.D., Nye, P.H., 1991. A model of ammonia volatilization from applied urea: the effects of steady-state drainage and evaporation. *Journal of Soil Science* 42, 103–113.

- Potter, C., Krauter, C., Klooster, S., 2001. Statewide inventory estimates of ammonia emissions from native soils and chemical fertilizers in California. Report prepared for the California Air Resources Board Emission Inventory Branch, Fresno, CA.
- Roe, S.M., Strait, R.P., 1998. Methods for improving national ammonia emission estimates. Presented at the Air and Waste Management Association Emission Inventory Conference, New Orleans, LA.
- Sutton, M.A., Place, C.J., Eager, M., Fowler, D., Smith, R.I., 1995. Assessment of the magnitude of ammonia emissions in the UK. *Atmospheric Environment* 29 (12), 1393–1411.
- Terman, G.L., 1979. Volatilization losses of nitrogen as ammonia from surface-applied fertilizers, organic amendments, and crop residues. *Advances in Agronomy* 31, 189–223.
- United States Department of Agriculture, Economic Research Service (USDA-ERS), 1996–1997. *Agricultural Resources and Environmental Indicators (AREI)*, 1996–97. *Agricultural Handbook No. 712*, Washington, DC.
- USDA, National Agricultural Statistics Service (USDA-NASS), 1997. Usual Planting and Harvesting Dates for US Field Crops. *Agricultural Handbook No. 628*.
- USDA-NASS, 1998a. Field Crops: Final Estimates 1992–97. *Statistical Bulletin No. 947*.
- USDA-NASS, 1998b. Noncitrus Fruits and Nuts: Final Estimates by States 1992–1997. *Statistical Bulletin No. 950*.
- USDA-NASS, 1999a. Citrus Fruits: Final Estimates by States 1992–1997. *Statistical Bulletin No. 961*.
- USDA-NASS, 1999b. Vegetables: Final Estimates by States 1992–97. *Statistical Bulletin No. 946*.
- Van der Weerden, T.J., Jarvis, S.C., 1997. Ammonia emission factors for nitrogen fertilizers applied to two contrasting grassland soils. *Atmospheric Environment* 31 (2), 205–211.
- Whitehead, D.C., Raistrick, N., 1990. Ammonia volatilization from five nitrogen compounds used as fertilizer following surface application to soils. *Journal of Soil Science* 41, 387–394.